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ABSTRACT

This paper describes a study of high school students' participation in the construction and revision of explanatory models as they attempted to account for a variety of inheritance phenomena observed in computer-generated "fruit flies". Throughout the course students were encouraged to explore epistemological issues related to the assessment and justification of knowledge claims (explanatory models) in genetics. Findings indicate that students' conceptions of models changed during the nine-week course. Initially the majority of students equated scientific models with proof of theories but by the end of the course, most students demonstrated understanding of the conceptual nature of scientific models and the need to justify such knowledge according to both its empirical utility and its conceptual consistency. (Contains 17 references.) (Author/WRM)

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ED 446 906

RESEARCH REPORT

NATIONAL CENTER FOR IMPROVING STUDENT LEARNING AND ACHIEVEMENT IN MATHEMATICS AND SCIENCE

USING A MODELING APPROACH TO EXPLORE SCIENTIFIC EPISTEMOLOGY WITH HIGH SCHOOL BIOLOGY STUDENTS

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University of Wisconsin-Madison

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Jennifer Cartier also works collaboratively with other Center researchers on The Modeling for Understanding in Science Education (MUSE) project. More information on this project will be posted at www.wcer.wisc.edu/ncisla in the Spring 2000.

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USING A MODELING APPROACH TO EXPLORE SCIENTIFIC EPISTEMOLOGY WITH HIGH SCHOOL BIOLOGY STUDENTS

Abstract

High school students in an elective genetics class participated in the construction and revision of explanatory models as they attempted to account for a variety of inheritance phenomena observed in computer-generated "fruit flies." Throughout the course, students were encouraged to explore epistemological issues related to the assessment and justification of knowledge claims (explanatory models) in genetics. For instance, lab group meetings that required the students to share their ideas while still in the formative stage helped to place the emphasis of their interactions on attempting to pinpoint conceptual inconsistencies underlying the models that weren't "working" rather than simply presenting empirical evidence for models that were complete. During the 9-week course, the students' conceptions of models changed: Initially the majority of students equated scientific models with "proof" (generally physical) of "theories"; at the end of the course, most students demonstrated understanding of the conceptual nature of scientific models and the need to justify such knowledge according to both its empirical utility and conceptual consistency. By extension, the students came to understand that the utility of models lies in their power to explain and predict natural phenomena rather than in their inherent ability to demonstrate "truth." In short, the modeling curriculum and instruction in this classroom enabled students to develop a more realistic view of scientific epistemology while they learned about important genetic concepts.

The nature of science as a modeling activity . U.S. policy documents such as *Benchmarks for Science Literacy* (AAAS, 1993) and the *National Science Education Standards* (National Academy of Sciences, 1995) are recent attempts, at the national level, to identify a set of desirable learning outcomes for pre-college science students. It was proposed that students who could master these learning outcomes would be considered scientifically literate—that is, they would possess familiarity with key scientific concepts and an ability to relate those concepts to their everyday lives in decision-making or problem-solving situations. Although there are currently several such educational reform documents, each of which articulates a unique set of learning outcomes or pedagogical commitments, most, if not all, of these documents have certain commitments at their core. Among these is a desire to incorporate meaningful discussions about "the *nature* of science" into science curricula. However, there is a great deal of vagueness and variability with respect to what is meant by "the nature of science" and what kinds of instruction and curricula enable students to engage with these ideas.

In an attempt to provide rich classroom contexts to teach about the nature of science, we, drawing from the work of others in science studies, have begun to problematize the notion of a *universal* nature of scientific inquiry (Gallison & Stump, 1996; Rudolph, 1998; also see Rudolph, date). In fact, we argue against teaching students about a universal nature of science as depicted in the formulaic descriptions contained in the introduction to most science textbooks. Instead, we feel it is most desirable to help them understand the day-to-day practice of scientists in particular disciplinary settings: As they study important concepts in a particular discipline, students should develop an understanding of the types of questions scientists in that discipline ask, the methodological and epistemological issues that constrain their pursuit of answers to those questions, and the ways in which they construct and share their explanations.

Although methodological and epistemological aspects of scientific inquiry can be discipline-specific, the construction of explanatory models to account for specified natural phenomena is a primary cognitive goal of scientists in many disciplines (Giere, 1988; Harrison & Treagust, 1998; Rudolph, 1998; Rudolph, in press). Once constructed, such models provide the basis for continued inquiry in the discipline. Generally speaking, explanatory models are continually assessed on the basis of how well and completely they can account for data and how consistent they are with other accepted models deemed important within a particular field of study (Cartier, 1998; Laudan, 1977). In some disciplines, models are also assessed based on how accurately they can predict the results of additional experiments. Consequently, empirical results as well as conceptual developments contribute to the iterative process of model development. The research described herein was conducted in a high school genetics classroom where one key intended learning outcome was that students appreciate how explanatory models for inheritance patterns were assessed on the basis of both empirical consistency (and predictive utility) and of the degree to which they fit within a larger context of conceptual knowledge in genetics.

Previous research on student understanding in this genetics classroom. Epistemological issues related to science traditionally have been given considerable attention in the classroom that was the setting for this research (see Cartier & Stewart, in press). Specifically, the class is a high school junior- and senior-level 9-week elective in genetics. The curriculum focuses on allowing students to build and revise explanatory models to account for a variety of inheritance phenomena that they experience with the aid of the computer program Genetics Construction Kit or GCK (Calley & Jungck, 1997). GCK enables students to generate populations of "fruit flies," make crosses with specified organisms, and keep records of the inheritance patterns associated with particular traits in each population. Working from an initial model of simple dominant inheritance, students encounter data incompatible with that model and experience the need to revise it in order to account for the new data. Through the iterative process of model revision and testing, the students construct explanatory models that can account for codominant, multiple-allele, and sex-linkage inheritance phenomena.

Past research in this classroom showed that students assessed explanatory models (their own and those of their classmates) primarily according to the empirical criteria of how well such models could account for data and predict the results of further experiments (Cartier, 1998). In

contrast to what practicing scientists do, students often failed to assess models based on how consistent they were with other accepted knowledge or ideas. For example, students were satisfied with a certain model that could explain and predict GCK phenomena associated with sex-linked inheritance even though the model in question was inconsistent with what they knew about equal segregation of parental chromosomes in meiosis. In other instances, students simply discarded models that couldn't explain data without attempting to discover the underlying conceptual problems with those models. In most cases, such problems involved inconsistency with meiotic processes such as segregation or assortment or with the process of fertilization. In this study, we also found that the students tended to view scientific models as physical representations of ideas (e.g., drawings, maps) or as verbal explanations rather than as conceptual tools for explaining natural phenomena.

In this report, we describe a subsequent study of high school genetics students' understanding of the nature of scientific models. Prior to this study, the genetics curriculum was altered to give students more opportunities to reflect on and discuss the nature of science as a modeling activity, and, consistent with actual genetic practice, to assess their own inheritance models on the basis of both empirical and conceptual consistency. We found that students' initial conceptions of scientific models reflected what we term "school science" notions; that is, the students felt that models were used in science to "prove" or "demonstrate" ideas. When students' understandings of models were reassessed at an intermediate point in the course and again at the end of the course, we found that their views had changed. Students discussed the ways in which models were used to explain data, and the need for their inheritance models to be able to accurately predict the results from new experiments and be consistent with other models or ideas they had discussed in class (specifically, a meiotic model and a molecular model of protein synthesis and protein function). Because this shift in understanding about scientific models occurred in the context of students learning about important concepts of classical transmission genetics, we suggest that an effective way to help students develop meaningful understanding of the nature of scientific practice is to make such ideas explicit while students are engaged in authentic inquiry in a particular discipline.

Research Design

Participants. The students who participated in this study were high school juniors and seniors enrolled in an upper-level elective science course. The high school enrolled approximately 500–600 students and served both suburban and rural communities near a midsized midwestern city. The 26 students in the genetics class had a variety of career objectives, ranging from attendance at a four-year college to immediate employment following high school graduation.

Data was collected from all 26 students in the course. Interviews were held with a sample of 7 students only. These seven students were chosen on the basis of availability and willingness to participate. Some effort was made to ensure gender equity, but only 3 of the 26 students

enrolled in the course were males. Consequently, the interview participants consisted of 6 females and 1 male student. Although these students were considered to be representative of the class as a whole based on both researcher and instructor evaluation, it should be noted that the average exam score for the interview participants was 74, whereas that of the class as a whole was 78—a small, but significant difference.

The teacher, a seasoned educational researcher herself, had more than 25 years of teaching experience and had been teaching the genetics course for nearly a decade. Development of the original course was part of her master's degree project and subsequent research on student problem solving in the course became the focus of her doctoral thesis.

The classroom setting. Expectations for student participation were outlined on the first day of class. The teacher told the students that the classroom would be modeled after an authentic scientific community in which all participants were coproducers of knowledge. The students were told that they would not be evaluated on facts they had memorized, but on the basis of their participation in formulating and communicating ideas. Along with their role as producers of knowledge, students were asked to be skeptical: They were expected to be critical of the knowledge claims of others, demanding evidence for claims and offering alternative interpretations where appropriate. Students regularly were asked to present their ideas as works in progress and solicit criticism and advice from others who were working on the same or similar problems.

In order to encourage students to consider the evidence and beliefs underlying their own knowledge claims and to keep track of their data and the evolution of explanations for that data, each was required to keep a notebook like that of a research scientist. On the first day of class, students were given a handout describing the laboratory notebook and guidelines for making entries. The notebook was described as "includ[ing] enough detail so that anyone reading it can repeat any experiment or be informed of any observations that were made and understand the reason for making them." The students were instructed to note what they "do, observe, and think" in the notebooks. The types of things students were expected to describe were listed in a chart, along with specific examples. In addition to descriptions of inquiries, the notebooks were used to record periodic journaling assignments. These assignments ranged in scope from questions about homework readings to reflections on classroom discussions and were used often to encourage students to think about issues that bear on the nature of inquiry in genetics. The notebooks were collected and graded on a weekly or biweekly basis.

The analogy of the classroom as a working community of scientists provided the structure for organizing student interactions throughout the course. Early on, research groups of 2–4 students were established. All small group discussions and inquiries were conducted with the students divided into these groups. Later in the course, sets of research groups were organized into two larger research teams. Each team was engaged in inquiry into a single multifaceted problem with the individual research groups that made up the team focusing on different aspects of that problem. Periodically, the students came together in lab meetings during which some groups would present data and tentative models while other groups would critique the models and offer alternative explanations or advice for further data collection. Informal meet-

ings also occurred between groups working on the same or similar aspects of the team problem. Having students hold meetings akin to scientific research group meetings helped to emphasize the importance of sharing ideas in their formative stage and enabled students to experience what was involved in the public justification of explanatory models. The theme of public justification of ideas took center stage in the culminating activity where students presented their models in a scientific poster session.

The curriculum. This genetics class has been described in detail elsewhere (see Cartier & Stewart, in press; Johnson & Stewart, 1990), and so the description here is succinct. The focus of this 9-week course was classical transmission genetics. Students began by making observations of different inheritance phenomena (such as fruit flies and human pedigrees) and recognizing various patterns in the data. For example, they examined pedigrees of families with heritable diseases (such as Marfan syndrome or cystic fibrosis) and identified empirical patterns associated with the inheritance of those diseases. They also observed fruit flies and noted the presence of both discrete (such as with eye color) and nondiscrete (such as with abdomen size) variations.

Next, the students read an edited version of Gregor Mendel's (1959/1865) *Experiments on Plant Hybridization*, in which he reported on his model for inheritance in peas. A graduate student playing the role of Mendel visited the students and together they characterized a number of generations of peas according to both shape and color, thus recreating the type of data sets upon which Mendel's original paper was based. Having done this, "Mendel" helped the students construct a representation of his model of simple dominance (Figure 1).

For the remainder of the course, the students used the simple dominance model, and revisions of that model, to explain inheritance patterns in computer-generated fruit flies. The computer program Genetics Construction Kit (GCK), designed by Calley and Jungck (1997), en-

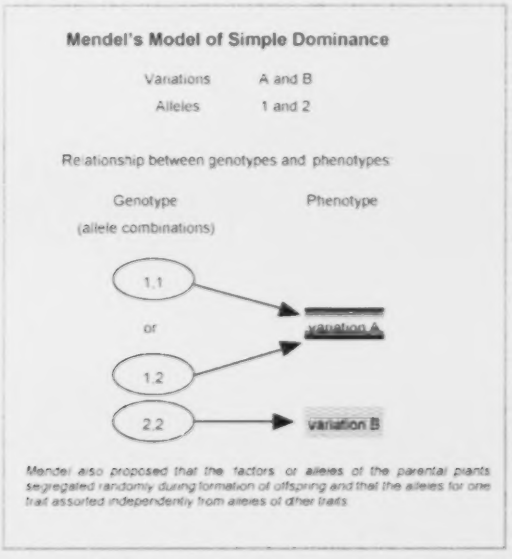
Mendel's Model of Simple Dominance
Variations A and B
Alleles 1 and 2
Relationship between genotypes and phenotypes:
Genotype
(allele combinations)
Phenotype
1,1
or
1,2
2,2
variation A
variation B
Mendel also proposed that the 'factors' or alleles of the parental plants segregated randomly during formation of offspring and that the alleles for one trait assorted independently from alleles of other traits.

FIGURE 1: MENDEL'S MODEL OF SIMPLE DOMINANCE.

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abled them to generate populations of "flies" and cross (mate) any two individuals in those populations while tracking the patterns of inheritance of particular traits. The students worked in research groups and held mock laboratory meetings to use and revise Mendel's simple dominance model in order to account for a number of inheritance patterns in their flies. In particular, the students constructed models to explain multiple alleles, codominance, and sex-linkage inheritance patterns and, in turn, used those models to explain the inheritance patterns they had previously identified in the human pedigrees.

In addition to their work with GCK, students also received instruction on meiosis, DNA replication, RNA synthesis and translation, and protein synthesis. Throughout the course, students participated in class discussions and activities (such as journaling assignments and the construction of concept maps) where they were encouraged to be explicit about their understanding of scientific models and the ways such models were related to their current work in genetics. These assignments and activities will be discussed further later in this report.

The students were evaluated on the basis of their notebooks and journaling assignments, their participation in group work (for which they received both an instructor and a peer grade), their performance on two exams, and their participation in a final scientific poster session where they presented one of their models to an audience of peers, researchers, and other school personnel.

Data collection. A researcher, in the role of participant-observer, was present in the classroom each day of the genetics course, compiling field notes. All written work generated by the students in the class, including their research notebooks, journals, exams, and final posters, was collected from each of the 26 students. Additionally, audio- and videotapes were made during lab group meetings and class presentations. Finally, seven students participated in a series of three open-ended interviews that occurred at the beginning, middle, and end of the course. The interviews lasted from 5–20 minutes and consisted of some general questions designed to elicit students' understandings of scientific models as well as the specific ways in which they used and assessed models in the genetics course. Knowledge claims are based primarily on students' written work (from notebooks and exams); researcher field notes, classroom transcripts, and interview data were used as sources for data triangulation.

QSR NUD IST 4 (Qualitative Solutions Research, 1997) software was used during coding to catalog and track students' developing ideas about scientific models. Specifically, students' journals and exams, as well as interview and classroom transcripts, were coded in NUD IST. Based on the results from our previous study (Cartier, 1998), we examined the data for evidence of students' understandings of scientific models. Some of our original codes and conceptual framework carried over from the previous study (e.g., we began by asking whether students understood models to be conceptual rather than physical entities) and other codes emerged from the students' own work in this study. Ultimately, we followed the development of students' understanding of several aspects of scientific models and also tracked the presence of alternative conceptions of models (see Table 1). Finally, we used our codes and framework from the previous study (Cartier, 1998) to document the ways in which students assessed their own inheritance

models in this study. Specifically, we focused on the ways in which students sought conceptual consistency between their models and other accepted models or knowledge in biology.

Randomly selected samples of student work were coded by a second researcher to ensure rater reliability.

Table 1. Features of Scientific Models and Alternative Conceptions

Features of ***Scientific*** Models	Alternative Conceptions of Models
• explain data/phenomena • are conceptual entities (ideas) • are consistent with other ideas • are agreed upon by a community • can be used to predict • account for a wide variety of phenomena and/or lead to reproducible results • change over time	• are demonstrations or proof of an idea • are physical replicas • visually represent an idea • serve as visual or conceptual teaching tools

Results and Discussion

Educators as well as lay people often use the term "model" to describe (among other things) physical replicas of objects or systems. This use would include, for example, a space-filling molecular model made of plastic as well as the material globes and light bulb that make up a "model" of the solar system. The term model is also used to refer to representational systems (e.g., maps or diagrams) and mathematical algorithms or formulae (Harrison & Treagust, 1998). Not surprisingly, researchers characterizing middle and high school students' views of models have also found that many students cite examples of "models" that are physical replicas, verbal or visual entities, and mathematical formulae (Grosslight, Unger, Jay, & Smith, 1991).

We recognize that these types of entities, namely graphical representations, formulae, and physical replicas, play important roles in the science and mathematics curriculum and are sometimes prerequisites to the articulation of scientific models by students. However, we take the position that they are not models themselves. In our view, one that has been informed by the science studies community (see Giere, 1988; Kitcher, 1993), a scientific model is a set of *ideas* that describes a natural process. A scientific model so conceived can be mentally run, given certain constraints, to explain or predict natural phenomena. Once constructed, models influ-

ence and constrain the kinds of questions scientists ask about the natural world and the types of evidence they seek in support of particular arguments.

In the high school genetics class described here, we attempted to help students develop a view of scientific models consistent with that described above. Specifically, we focused on the conceptual (versus physical) nature of scientific models, their utility in explaining and predicting data, and the need for such models to be consistent with other models and ideas in science. We also emphasized that, although models are used to explain data, the data themselves are not a part of the model. These ideas about the nature of scientific models and the ways in which such models are assessed were addressed explicitly throughout the course. Our study focused on students' understandings of scientific models prior to, during, and at the end of this course.

Students' early views on scientific models. During the first two weeks of the genetics course, the students made a number of observations of fruit flies and human pedigree data in order to become familiar with types of variation and inheritance patterns for such variation. During the second week of class, the students developed (with the help of a graduate student posing as Mendel) a representation of Mendel's model of simple dominant inheritance. After a few days of using "Mendel's model" to explain the inheritance of "fruit fly" traits in GCK, the teacher asked the class to work in groups of three to brainstorm ideas about scientific models. She introduced the activity by noting that they had spent several days working with Mendel's model without giving any thought to the term "model" and what it meant to each of them.

The students worked in their small groups to brainstorm ideas for about 15 minutes and then returned to the large group. The teacher asked students to share their ideas about models with the class, and, while students offered suggestions, she compiled them into a list on the overhead projector. First, the teacher wrote:

> What is a model?

Students offered the following ideas:

- "Shows an idea"
- "Is a proven fact"
- "Solve a problem with it"
- "Can be used by others to produce the same results"
- "Has to explain your hypothesis with facts and results"
- "Get same outcome every time"
- "Answers a question"
- "Eventually has to be widely accepted"

Next, the teacher wrote:

> How are models used?

Students suggested the following uses for models:

- "Visual understanding/greater understanding"
- "Help other people understand your theory"
- "Apply a model to real life situations"
- "Easier to see if it's three-dimensional"

From these initial responses, it is clear that several students thought of models as visual/physical representations used to enhance their understanding of certain ideas. Such a view of models is inconsistent with our own, but is entirely consistent with the ways in which physical props traditionally are used to demonstrate ideas in school science. In their initial interviews (which occurred during the first week of class and prior to the discussion described above), several students recalled prior experiences with models in science classes. Most of these students equated models with classroom demonstrations of scientific concepts. One student, Andrew, described at length a machine that used forced air to propel ping pong balls around in a steel cage. This demonstration had been used in the ninth-grade integrated science class to illustrate key features of the kinetic molecular theory: How molecules collided with one another with increasing frequency when they moved at increased velocity and so on. Andrew remembered the machine vividly and even recalled some of the underlying principles of kinetic motion being illustrated. However, he clearly identified the machine itself, and not the kinetic molecular theory, as the model. Moreover, he went on to describe another classroom demonstration (using special glasses to view prisms) as a model:

Interviewer:	For today, I just wanted to start off by asking you about your past science classes here. Do you remember talking about models in any of your other science classes?
Andrew:	Uh huh. Somewhat—
I:	Do you remember—I was just asking [your teacher] about this—the kinetic molecular theory?
A:	Yeah.
I:	You remember that model?
A:	Yeah, I remember that one.
I:	OK. There are a couple [of] others that you talked about. And I'm wondering if you consider all these scientific models, what are some of the parts that they have in common that you think are important parts of being a model? Some things about them?
A:	No. I can't really think of anything that would be important. I don't know. Interesting. I think that's the importance of the model. Like for teaching? In relevance for teaching kids and how to get them to learn. I don't know—maybe. 'Cause I remember the ping pong ball being so interesting, and you know, something different to look at you know. It just like took up a whole class period. Just like looking at ping pong balls. It was just kind of interesting, you know? Something different.

I: What did you do exactly? I'm not familiar with what that looks like in the classroom.

A: Well, yeah, it was like this huge mach— [started to say "machine" but cut himself short] —like, crate full of balls, and then they'd just turn it on, and it would bounce these ping pong balls around. Then they'd like take some out, and it would show how the frequency that, like, the red ones would hit red ones would be like [pause] and if they sped it up or made it faster then, like, the frequency would get higher. You know—

I: Right, OK. So it was like a ping pong ball machine?

A: Oh, it was like a big crate. Like as big as this table like. Big! And there was like a whole bunch of ping pong balls in it, and some of them were colored, and some of them weren't. And I think they, like, gave a ping pong ball to each person, and they had to try and count how many times their ball hit another ball or something like that.

I: OK. And this was a model for what?

A: The kinetic molecular theory. You just told me that, that's why I remember!

I: Right, so what you remember about it is the ping pong ball machine, but the rest of it [pause] you don't remember it so well?

A: I don't remember why we studied it or anything like that. I just remember what we were talking about. How like if things heated up then they'd like move faster and if it was colder then they'd slow down. And the rate at which the particles would hit each other and then the forces exerted from that.

I: That's it. That's great. So we've got the kinetic molecular theory model, and we've got the solar system model. Do you think those are good models?

A: Yeah. I remember another model we looked at that was kind of fun, too. They gave out these glasses, and they were like spectrum glasses. I remember that was a fun lab.

I: What were the spectrum glasses?

A: They handed out these glasses. And they'd, like, you'd, like, look at lights and different stuff, and they'd divide the light into a spectrum. Those were neat, actually.

I: Were the glasses a model for something?

A: Yeah. We were talking about the spectrum and the division of light. Stuff like that.

I: OK. So, and you thought that was a good model, too?

A: Just cause it was interesting. Yeah. Something differen'. I think the monotony of the everyday class period is what really gets me.

I: OK. So, can you tell me if you think these are good models? Is there anything special about them besides the fact that they're interesting that you think makes them good?

A: I think they actually, like, learn from it. Like, I remember getting an idea from that ping pong machine, like, of how it actually worked. And, like, by speeding it up, you know? Although I already pretty much understood the concept and what they were trying to teach us. Kind [of] reinforcing it, I guess.

Andrew's classmate, Elizabeth, also remembered the ping pong ball machine as a model because "it was a visual representation of how things actually work." For Elizabeth, like many of her classmates, it was highly desirable for models to "be easy to understand [and] explained well," and quality visual properties of models facilitated such understanding. Another student, Michelle, put it this way:

Michelle: I think, most importantly, [a model] has—the people you're showing it to, or the person who's trying to get something out of it, has to see it. It has to be clear to the students or just clear to the person you're showing it to or the people you're showing it to.

I: And what kinds of things would make it clear?

M: Um, ideas. Or pictures. If there are pictures on it that showed it. . .a good model I guess would have to be clearly understood.

In the class discussion, students also noted the role of a community in accepting scientific models and the need for models to be consistent in their application. Although it is unclear from these responses whether students were thinking of models as a type of problem-solving algorithm, experimental protocol, or explanatory framework, the initial responses of students suggest that they held different, sometimes conflicting, views of scientific models.

Following this class discussion, the teacher noted that she merely compiled a class list of ideas without assigning value to any one idea. Then she asked the students to answer two questions in their journals for homework:

> What is a scientific model? How are scientific models different from other types of models you've talked about or heard of in the past?

As expected, the students' journal responses were consistent with the ideas they had voiced in the class discussion. By far the most common view expressed by the students was that of model as a demonstration or proof of an idea. Nineteen of the 26 students wrote about the use of models to teach or prove an idea or theory:

> A scientific model is something which proves someone's theory to a scientific problem. . . . *(Emma)*

> A scientific model is something that is shown in order to explain a scientific theory . . . a scientific model is a proven fact of something and often is a representation of the results of a scientific experiment . . . *(Melissa)*

> A scientific model has to explain an idea . . . it should be accepted as factual by other scientists to be considered a true model. It should be fairly simple and easily explained. (*Susan*)

> A scientific model is something that is used to explain a certain idea or answer a question about something. . . . the model needs to be a representation of something and promote understanding about it. (*Danielle*)

> . . . it promotes an understanding and shows proof that the idea is correct. (*Linda*)

Several of the students, including Susan above, also wrote about the social aspects of scientific models, indicating that a group of colleagues played an important role in assigning "factual" status to models. Although we also acknowledge the importance of peer acceptance in the construction and justification of models, we believe that the role of the scientific community is not to judge the truthfulness of models, but rather their explanatory/predictive adequacy and conceptual consistency. Consequently, the views expressed by these students early in the course are only partly compatible with the realistic understanding of science as a modeling enterprise that we were attempting to teach.

Even this early in the course, some students did hold views of scientific models that were quite close to our own. These students recognized that models were used to explain data and that the fit between a model and a particular data set was an important quality. Sometimes they were also explicit about the distinction between physical representations and the conceptual models underlying those representations:

> A model is a way to explain phenomena. A model is usually created in order to explain some data that has been collected. The model should hold consistently for all situations, and could be used to predict results in future situations. A model is an idea, not necessarily a physical representation. However, a drawing or physical object can be used to communicate the idea to other people. (*Amanda*)

> A scientific model is something that can explain a question or problem. It is something that you can come up with by looking at similar problems or situations, then making a model that you think will fit all situations like that. A model summarizes a reason for observations you've made. (*Anita*)

However, only 5 of the 26 students described models in terms that were entirely consistent with our definition of *scientific* models. Fifteen others expressed views that were at times directly conflicting, that is, they were in some respects consistent with an understanding of scientific models and in other respects more representative of a "school science" understanding of models as physical demonstrations of ideas. Table 2 summarizes some key aspects of students' early views of models.

TABLE 2: SUMMARY OF STUDENTS' EARLY VIEWS ON MODELS

Scientific View	*School Science* View	*Other (or unclear)*
A model is an idea that scientists use to explain natural phenomena and predict the results of future experiments. The model must be able to explain a variety of related phenomena. A community of scientists must agree about the usefulness and acceptability of a model.	A scientist used a model to demonstrate or offer proof of an idea. Teachers frequently use models, or visual representations, to help students understand scientific hypotheses.	Models "contain" data. Models must produce or "give" the same results each time.

Students' developing views of models. Following their class discussion and journaling assignment about the nature of scientific models, the students were given a handout (See Appendix) that described models as "explanation[s] of how we think some part of our world works." The handout also discussed the ways in which models are assessed—namely for explanatory and predictive power and conceptual consistency. After they read the handout, the students had a brief class discussion where they noted the ways in which their journal responses were similar to and different from the view of models described in the handout. Throughout the course, the teacher attempted to use the modeling language developed in this handout whenever possible and also to explicitly discuss the use and assessment of the students' own genetic models wherever appropriate.

For about a week after this initial instruction on the nature of models, students worked with their simple dominance model to explain the inheritance of traits in GCK-generated "flies." Once they had mastered the use of the simple dominance model, the teacher asked them to construct a concept map to synthesize ideas about Mendel's original model, the inheritance patterns they had been noticing in fruit flies and human pedigrees, and the nature of scientific models. The students were given instructions on how to create concept maps (See Appendix) and asked to place the following terms, as well as two of their own choosing, into a concept map:

dominant	gene	pedigree
recessive	data	model
fruit fly	trait	variation
segregation	(1,1)	allele
phenotype	genotype	yellow peas

Each student created his or her own map as a homework assignment. The following day, students worked in groups of six to create "consensus" maps that represented, to the extent possible, a summary view of the relationships between key terms/concepts. In addition, the students were asked to divide their work space into a "realm of ideas" and a "realm of observations" and to place their maps onto this space in an appropriate orientation. In other words, the students needed to represent the relationships between terms in the map and also indicate whether each term was an idea or an observable phenomenon.

During the next class period, students shared their maps and attempted to identify commonalities and important differences. One issue the students had difficulty resolving was whether the concept "model" should be located in the *observation* or the *idea* part of the map. One student explained that "we put it [model] under both [observations and ideas], because [pause] because the way we defined the model in our class it was something like it was an idea of something. So you could show people your idea." In response to this comment, some students suggested locating the term "model" right on the line separating observations from ideas in the maps. Another student, Jennifer, protested that a model is *just* an idea. To illustrate her point, she described a space-filling representation of a molecule and noted that the physical balls and springs were just a way of communicating the underlying idea of molecular structure. This comment in turn, sparked a rich debate about the nature of models:

Jennifer:	The only way you'd really be able to see your model is you stuck the little balls and springs together and made little molecules or [inaudible] . . .
T:	So those balls and springs aren't your model?
Student 1:	[inaudible]
T:	What are they?
Jennifer:	It's just a representation of the idea.
S1:	They can be part of your model sometimes.
S2:	That's kind of what we thought.
T:	OK. Yeah, well, let's decide. What's the model?
S1:	The idea.
T:	The idea, or the representation of the idea?
S1:	It's both.

S2: I think it's both.

T: OK, in the past—

S1: In order to have the representation of the idea, you have to have the idea first. So if you're going to use your model and say, "This is my model," and show somebody something, you had to have the idea behind it, so it's both.

S2: You're representing what you, by what you're showing, that means you're representing the idea. You show somebody your model, then that's the idea you're representing.

S3: [inaudible]

S4: But what's the observation that comes up with your model?

S1: Any model.

S2: If you want to print your model, then you have to put it under observation, but if you don't, it can just stay under ideas.

T: OK, so in other words, you can have a model that's an idea. But if you want to communicate it to the people, somehow you have to represent it.

This discussion marked a shift in students' thinking about models generally. Earlier in the class, the majority of students expressed views of models as physical representations or demonstrations of ideas. Now, in the middle of the course, students were explicitly talking about models as *both* representations *and* the ideas underlying such representations. As the teacher summarized, the students were beginning to see that "you can have a model that's an idea. But if you want to communicate it to the people, somehow you have to represent it."

A few days after this activity, the students took their first hour exam. Two of the questions on the exam—one a short answer essay question and the other a concept map and essay question—explored students' views of models in general and how the Mendel model of simple dominance in particular had been used and developed (both questions are shown in full in the Appendix). Students' answers to part D of question 2 and all of question 3 were coded for evidence of their understanding of scientific models.

Students' responses to the exam questions were quite consistent with the views they had expressed only a few days earlier during the class concept map discussion. Nine students described Mendel's model of simple dominance as an idea that explained his pea plant data but later contradicted that view by describing models as demonstrations of ideas. For example:

[consistent with a scientific view of models]

> It [the 'Mendel model'] is what Gregor Mendel showed to explain how variations of traits are passed on from parent to offspring. It shows that the offspring gets a variation of one of the parents, not a combination. . . . The Mendel model can be used to explain pedigrees. He explained pedigrees of pea plants using his model. He explained it using his definition of dominant and recessive variations. *(Susan)*

[consistent with a school science view of models]

> Scientific models use data to prove that what they show is true. . . . The scientific model . . .[is] both observations and ideas. (*Susan*)

Similarly, five students identified data as part of a model while simultaneously indicating that models are ideas:

> A pedigree is a form of data . . . . A pedigree is a Mendel model because it deals with dominance and recessives. . . . I put all of the models . . . under ideas because a model is considered to be made up of thought. (*Jake*)

> As you collect data from research that you are doing, some of the data could be part of a scientific model. . . . I placed the line where I did because data and pedigrees were both things that you observed after you had gotten an idea. All the models were ideas that you had . . . (*Melissa*)

Although several students still expressed conflicting views about models, the class as a whole seemed to shift its understanding of models from one of "school science" to one that was more "scientific." Recall that at the time of the early measurements, only five students expressed views of scientific models that were completely consistent with those we set out to teach. Based on their performance on the first exam, that number had increased to seven. More importantly, there were no students whose views could be characterized as completely consistent with a school science perspective, down from four students in the early measurement. Also on this exam, eight of the students described the need for consistency between Mendel's simple dominance model and the meiotic model. In their initial interviews, discussions, and journaling assignments, no students mentioned the need for models to be consistent within a scientific discipline or a context of scientific knowledge more generally. The need for models within the discipline of genetics—all of which share some underlying concepts such as the mechanism of segregation—to be conceptually consistent with one another is an important component of a scientific view of models.

Students' views on scientific models at the end of the course. After the first exam, the students spent about three weeks working in research teams to revise Mendel's simple dominance model in order to explain anomalous inheritance patterns in GCK organisms. Each team studied the inheritance of four traits, each of which displayed a unique inheritance pattern (simple dominance, codominance, multiple alleles, or sex linkage). Students met regularly in their research teams to discuss their ideas, share data, and so on, and presented their final models in a classroom poster session. Throughout these few weeks, the teacher continued to remind the students that their models needed to be able to explain and predict data as well as be consistent with other models. One required element in the poster presentation was for students to discuss how their ideas/models had changed while they attempted to revise the simple dominance model and to be explicit about the reasons for those changes. Students mostly discussed

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models discarded on the basis of inability to explain data, but some students also mentioned models inconsistent with meiotic processes.

At the end of the course, the students took a second hour exam, and some students participated in a final interview. The final interview responses indicated that students' views of models changed significantly during this 9-week course. Most students now recognized that models were used to explain and predict data—a change from initial views of models as proof of ideas or demonstrations of facts. When asked in the final interviews what were some important aspects of scientific models, students replied:

Amanda: OK I'm a little better prepared this time. It has to explain all the data you have. It has to be able to predict data, future data. It probably has to work physically, with like, it has to fit with previous knowledge of anatomy or whatever.

...

Elizabeth: I guess it's got to explain the observations that you already made and then also help predict what would happen if you got more data. It has to be reliable. It has to pretty much always work. But I also think you would need to take into account all of the levels of science and since I don't know anything about meiosis or anything like that I don't think I could make a good model.

Interviewer: All the levels of science?

E: Well, you know it has to—the whole molecular level—and you have to really have an understanding of everything that you're working with. I'd really need to know more about fruit flies before I could come up with something that I think would work. For all I know, they could have some sort of weird mating pattern . . .

...

Alissa: Um. That it needs to be understandable by people outside of the peer group. Or at least somewhat easily explainable.

I: OK.

A: That it works. [laughter]

I: Tell me more about "that it works."

A: That when you put the, er, cross the pairs that you get the kids that you're expecting or that it [inaudible] or [inaudible]

...

Melissa: Um. If it can explain what you're trying to determine. Um. If you understand it well, and it fit with the data. Um.

In short, the students seem to have developed a more mature scientific epistemology, shifting from an expectation of scientific *proof* to one of explanatory power or data/model *fit*. Initially students described the ways in which data were brought to bear in proving theories.

However, at the end of the course and perhaps due to their own experiences with modeling, students described ways in which models were brought to bear in making sense of data:

Early journaling assignment:

> I believe that a model shows an idea or *proves* a theory . . . *(Monica)*
>
> [Emphasis added]

Exam 1:

> These [models] all explain or interpret. An idea of how something works. Although all seem to be able to be supported, *none can be proven true. (Monica)*
>
> [Emphasis added]

It is interesting to note that this shift away from seeking proof in science toward offering empirical support for scientific models was never explicitly addressed in class. Rather, it seems to have been a natural consequence of the students' own experiences revising and justifying genetic models.

What students understood about models in context: How they revised and assessed their own inheritance models. On the final exam question, students were asked to consider the relationships between terms in the concept map below (Figure 2) and discuss the ways in which those relationships influenced their own work on the final GCK problem.

Students' responses to this question showed that they understood the ways in which Mendel's simple dominance model had been brought to bear in explaining their own data. All but three of the students talked about the need for their final models to explain all of the data available to them, and 19 students also described specific ways in which they used models to predict the results of additional experiments:

> Our model, as can be expected, was based heavily on the GCK data received from specific crosses. Our model's relationship to the data is that it was formed from data and fits that data to explain and predict. *(Cathy)*
>
> We tried developing a number of models to explain the GCK data from our computer crosses. We needed to develop a new model because the results from our crosses were different than any other results we had seen. We knew that the outcome had something to do with the sex and variation of each of the parents. After our first few models failed to explain our data, we decided to give the males only one allele for each variation, and this explained all of the computer crosses we had done. *(Anita)*

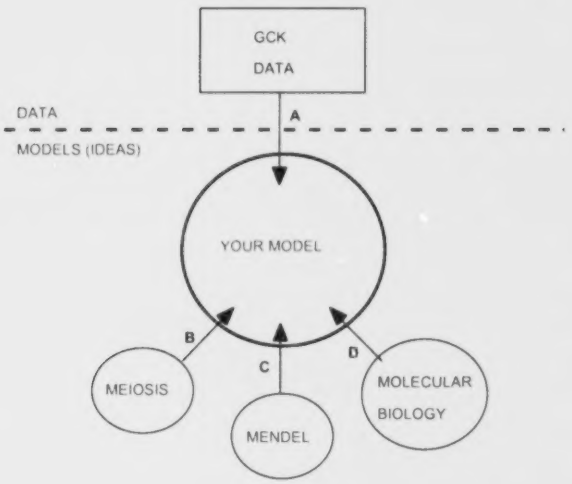

FIGURE 2. CONCEPT MAP FROM EXAM 2

Up to this point, we had not gathered much evidence to indicate that students appreciated the need for this family of genetic models to be consistent with one another and also with meiotic and molecular biological processes. On the first exam, eight students mentioned that Mendel's model and the meiotic model were consistent with one another because they shared the underlying processes of segregation, and so on. In this second exam, however, students were asked to talk explicitly about the ways in which they had considered consistency issues while revising Mendel's simple dominance model. Seven students talked about the ways in which their understanding of molecular biology and protein function influenced their modeling, and 12 were explicit about the connections between meiosis and their revised models.

We found these connections to be quite exciting for a number of reasons. First, our previous research indicated that students tended to have difficulty recognizing issues of conceptual consistency while modeling and such difficulties contributed to a lack of success in constructing models with adequate explanatory power (Cartier, 1998). Second, assessing explanatory models based on how well they fit with existing knowledge is an integral part of scientific practice in genetics and other disciplines. Consequently, it is desirable in and of itself for students to experience this aspect of inquiry. However, it also appeared to help them to come to a deeper understanding of the nature of science as a modeling activity: Students learned how to assess models in science in part by participating in appropriate assessments of their own models. Finally, as their exam responses show (see Table 3), paying attention to consistency issues helped students synthesize their knowledge of several ideas into a rich understanding of classical transmission genetics.

TABLE 3: STUDENTS' RESPONSES TO FINAL EXAM QUESTION:
How Valuing Consistency Among Models Helped Students Build a Deep Understanding of Genetic Concepts

STUDENTS' RESPONSES	COMMENTS
The concept of meiosis helped us keep in mind that all traits could have only two alleles per offspring unless the trait was X-linked. It helps to explain how the parents are used to determine the genotypes of the offspring. *Monica*	Consistency with the processes of segregation and fertilization.
In our model for eye shape, sparkling was a 1,1 or 1,3 and was codominant over roughoid with darks (which was a 2,2, or 2,3). Then on one side was star, a 1,2. It was confusing at first for us to understand how a 1,2 could be different from the 1,1 & 1,3 (sparkling). Now I understand that the 1,2 codes for proteins 1 and 2, and obviously protein 2 has an affect [sic.] on the organism which is different from how protein 1 affects it. This is what creates codominance. As for sparkling (1,1 & 1,3), the 3 doesn't affect the organism when a 1 is present also–a 1,1 and 1,3 have the same appearance. But the 3,3 only has the 3 so the organism can only be affected by 3. It is very helpful to understand our model on a molecular level. *Denise* [emphasis original]	Knowledge of protein function enabled Denise to "see" how the allelic combinations in her model could result in the observed phenotypes.
Our model had to be consistent with the meiosis model. Since meiosis says that each person has 2 alleles and passes one on to its child, we had to restrict ourselves to giving each individual only 2 alleles instead of 3 or 4. If the model weren't consistent with meiosis, there would be no way to explain the physical process of inheritance. Molecular biology was also important to our model. It helped us explain why we could add a 3rd allele to explain our crosses. Since an allele is a different sequence of DNA, molecular biology dictated that there is no reason why we couldn't have as many different sequences of DNA as we want. *Amanda*	Consistency with the processes of segregation and fertilization. Knowledge of DNA structure and function, as well as protein synthesis, enabled Amanda to understand that having multiple alleles in a model could result from a number of different DNA sequences which, in turn, coded for different proteins.

Conclusion

In summary, we found that the students in this genetics class initially held views of models that were consistent with a school science perspective: They considered models to be demonstrations and empirical proof of ideas. By engaging in activities and discussion about the nature of models and also by constructing and revising their own models of inheritance, the students gradually developed a view of models consistent with our own: They came to see that a model is a conceptual entity the utility of which lies in its ability to explain and predict data. Moreover, scientific models must be consistent with other accepted knowledge in a discipline.

But students did not only learn about the nature of scientific models. By structuring this genetics course around opportunities to conduct authentic inquiry, we were able to engage students in the construction, revision, and assessment of their own models. Our data show that students understood the need for consistency among models (see Table 4). We also observed that the majority of students paid attention to consistency issues when constructing their *own* models and were able to discuss the specific ways in which their knowledge of meiosis and molecular biology were brought to bear in that process (see Table 3). Moreover, we view this knowledge integration as evidence that students were able to come to a rich understanding of genetics—of both the central concepts of transmission genetics and the important aspects of genetic practice.

TABLE 4: EVOLUTION OF STUDENTS' CONCEPTIONS OF MODELS

Conception of Model	*Students' Conception During Course* Early (%)	Intermediate (%)	Late (%)
"Scientific"			
Models are ideas	23	95	100
Models are used to explain or predict data	35	95	83
Models need to be consistent with other models/ideas	0	32	83
"School Science"			
Models are physical/visual replicas of ideas	42	0	0
Models are used to demonstrate, prove, or teach ideas	73	63	15

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Appendix: Thoughts on Scientific Models. . . [Handout]

Yesterday we spent some time compiling our thoughts about models in general and each of you went home and wrote about scientific models specifically. Our aim (if you'll remember) was to decide upon what we mean when we talk about the "Mendel model" and other scientific models in this genetics course. Here we describe what we accept as a definition of "scientific model" for the purposes of this course. (Remember that there are many uses of the word 'model' and that no one meaning is 'right' while others are 'wrong'. However, for the purposes of this class, the single meaning of scientific model is discussed below.)

One kind of scientific argument involves the development of a scientific model. A scientific model is simply an explanation of how we think some part of our world works. If you remember from chemistry, our model of the atom, for example, consists of protons and neutrons surrounded by various shells of electrons. This atomic model helps us understand why certain atoms combine with others in chemical reactions, how static electricity can result from the accumulation of charged electrons on some surfaces, etc.

It is important to understand that the scientific model here is not the picture in your textbook of protons and neutrons surrounded by electrons, nor is it a physical model that you can hold in your hand. The scientific model is simply the idea that particles such as protons, electrons and neutrons exist and behave in predictable ways. A collection of these ideas (scientific models) can be thought of as a scientific theory.

Protons, neutrons, and electrons, in this sense, are not necessarily real. They are ideas that humans have thought up to help explain what they have seen or the data they have collected. Since they were invented by scientists, it is important to question whether or not they really do help us understand the world. It is in this sense that these scientific models are arguments. Now, the atomic model as an argument is particularly strong. It has thoroughly convinced all scientists that the idea of matter being composed of atoms is particularly useful, if not real or true (though, as you have seen in the many black box activities you have encountered in the science curriculum at Monona Grove, you never know whether or not any model is really true).

Scientists are not the only ones who need to question whether or not a given scientific model is really useful in helping us understand what we see in the world: you must also learn to evaluate the usefulness of models according to scientific criteria. Specifically, you will notice that a model should be able to explain all the data about which it makes a claim. If we could use the atomic model to explain why hydrogen and oxygen bond to form water but not how sodium and chloride combine to form salt, it would not be a particularly useful model. In fact, the atomic model can be applied broadly to explain the interactions between all the atoms and thus is a very powerful model. Another example is the Mendel model: we found that Mendel's model can explain the inheritance of traits in pea plants. However, we also found yesterday that Mendel's model could explain the inheritance of Marfan syndrome in humans. Thus, we have shown that Mendel's model has broad explanatory power.

Another criterion for evaluating scientific models (both their usefulness and our satisfaction with them) is whether or not they can help us correctly predict what we might see in the world given certain conditions. According to the atomic model, we would predict that the precipitate in a solution of sodium and chloride ions contains sodium and chloride in equimolar amounts (in other words, one sodium and one chloride ion bond to form a salt). If we were to analyze such a precipitate, we would find that the prediction was correct, illustrating the predictive power of the atomic model. Thus far, we have had limited experience using the Mendel model to predict the outcome of particular hereditary events; however, during our discussion of the pedigrees, someone made the comment that she couldn't tell whether the Mendel model fit with the Marfan pedigree data because she didn't know what would happen "when we crossed two red people". In other words, she was beginning to think with the model about the expected outcome of a given cross. Had that cross produced the results (data) she predicted using the Mendel model, she undoubtedly would have agreed that the Mendel model was useful for thinking about the inheritance pattern of Marfan syndrome.

Finally, we must also realize that any one scientific model coexists with many others, as well as with all of the other types of knowledge and beliefs we hold. Thus, our judgment of how well any model fits with (or is consistent with) the rest of our accumulated knowledge is another way in which we decide how useful and satisfactory a model is.

We will continue to discuss models and how we evaluate them as this course proceeds. For now it is important that you understand our definition of model as it is put forth here and that you strive to consistently question the knowledge claims made in this class.

Appendix: Instructions for the Concept Mapping Activity [Handout]

Tomorrow we will spend some time reflecting on the work we've done to date in this class, paying particular attention to the connections that exist between the ideas and phenomena we've explored. **In order to fully participate in tomorrow's class, it will be important for you to spend time thinking carefully about and completing the assignment below.** You should also be prepared to hand in your work when asked to do so.

Creating a Concept Map

A "concept map" is a diagram that portrays the relationships between ideas or objects. Generally, the ideas or objects are represented as bounded shapes (ovals, squares, etc.) on the map and the relationships between those ideas are drawn as lines or arrows connecting the shapes. Thus, the shapes are analogous to locations on a map and the lines are analogous to the roads that enable travel from one location to another.

Concept maps are useful tools for exploring and talking about a variety of ideas. There is no "correct" way to construct any given map: each map depends upon the ideas of the person making it. The two maps shown to the right illustrate how different individuals will see and represent the relationships between the same set of concepts differently.

Assignment

Create a concept map using the terms in the list below and any others you feel are appropriate or necessary to convey your ideas fully. *You must add at least 2 terms of your own choosing to the list below!* Your map should portray what you feel to be the relationships between the ideas/objects in the list. Remember to use lines to represent connections between ideas/objects and to label those lines with a description of the nature of those connections.

dominant	gene	pedigree
recessive	data	model
fruit fly	trait	variation
segregation	(1,1)	allele
phenotype	yellow peas	genotype

Appendix: Exam 1 Modeling Questions

2. You are at home, diligently studying for your Genetics exam, when your younger brother walks into the room to borrow your new CD. He notices your copy of 'meticulous Mendel' lying out and is curious about it. Since he's taking Science II now, he's familiar with some of the terms and ideas of genetics, but is a little confused about the specifics of your Mendel Model. In the spaces provided, explain what you would tell your brother in order to clear up his confusion when he asks the following questions:

[Remember–you want to be as clear and detailed as possible so he will no longer be confused. You are not just trying to answer quickly and get rid of him!]

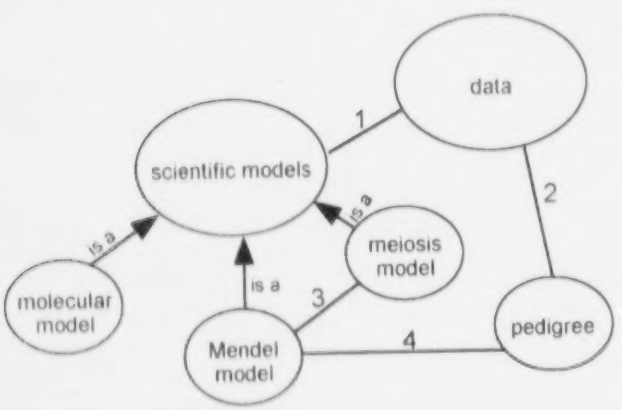
a. Oh yeah! I kinda remember this stuff from earlier this term. What's the difference between genotype and phenotype again?

b. What's with all the 1's and 2's? What are they supposed to stand for anyway?

c. What does 'segregation' mean? Does that have anything to do with meiosis or something? 'Cause we're just starting meiosis now.

d. Why do you call this the 'Mendel Model'? What's it supposed to be a model for?

3. Below is a concept map that represents the relationships between specific models, models in general, data, etc. Use the map to answer the questions below it.



a. Remember that a line in a concept map represents a relationship between two terms (concepts, ideas, etc.) in the map. Write a few sentences below that describe the numbered relationships between the terms given. Be as specific as you can: use the appropriate vocabulary of genetics to make your point as clearly as possible.

1.

2.

3.

4.

b. Draw a line (not necessarily a straight one) to separate the world of ideas from that of observations on this map. Please label both sides. Justify your placement of that line.